

A MATLAB TOOL FOR THE CHARACTERISATION OF RECORDED UNDERWATER SOUND (CHORUS)

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The advent of low-cost, high-quality underwater sound recording systems has greatly increased the acquisition of large (multi-GB) acoustic datasets that can span from hours to several months in length. The task of scrutinizing such datasets to detect points of interest can be laborious, thus the ability to view large portions of the dataset in a single screen, or apply a level of automation to find or select individual sounds is required. A toolbox that can be continually revised, the user-friendly “Characterisation Of Recorded Underwater Sound” (CHORUS) Matlab graphic user interface, was designed for processing such datasets, isolating signals, quantifying calibrated received levels and visually teasing out long and short-term variations in the noise spectrum. A function to automatically detect, count and measure particular signals (e.g. blue whale sounds) is integrated in the toolbox, with the ability to include categorised calls of other marine fauna in the future. Sunrise and sunset times can be displayed in long-term average spectrograms of sea noise to reveal diurnal cycles in the vocal activity of marine fauna. A number of example studies are discussed where the toolbox has been used for analysing biological, natural physical and anthropogenic sounds.

INTRODUCTION

The underwater “soundscape” comprises the combination of sounds of natural physical, biological and anthropogenic origin at a given location, and offers significant information on the local environment and its vocal inhabitants. Reports of soniferous behaviour by species, previously undocumented as vocal, are published consistently, highlighting how much can be learned from underwater passive acoustic observations, but also that there is still much more to discover by such means. In Australian waters, for example, cetaceans [1-4], fish [5-8], invertebrates [9-11], to name a few, all contribute to the soundscape. Along the coast, physical contributions to the soundscape are dominated by the sound of breaking waves or surf. Rain also generates consistent broadband noise during periods of heavy rainfalls. Anthropogenic activities, whether vessel use [12], offshore oil and gas exploration [13], construction and operation [14], or general horseplay [15] generate intense impulsive and tonal underwater sounds.

Natural and man-made underwater sounds can be impulsive or continuous signals with broad or narrow frequency bands and can contain frequency components from fractions of 1 Hz to several hundred kHz. They can occur individually, or so frequently that together they mask all other sounds [16]. The quantification of sound’s acoustic characteristics, such as the sound source level, peak frequency and duration [8, 16, 17], can help understand the relationship between marine fauna and their acoustic environment, and the impacts anthropogenic sound has on that relationship. Periodic increases in sound pressure levels (SPLs) from biotic sounds can be indicative of multiple animals present, such as the choruses of vocal fish [18, 19] and whales [20]. These SPLs, or individually counted calls can be a proxy for the abundance of the calling species in the area

[3, 21, 22]. Thus temporal patterns in the spectrum level of sound production can offer information on the temporal presence at the recording location and, if associated with influential factors in the local environment (temperature, salinity, anthropogenic noise), provide information on the responses of vocal fauna to such drivers of presence and absence [18, 19]. It is the long-term comparisons of these contributors to local ambient noise, or soundscape, that offers us this information and is becoming more readily accessible to those that study it.

Advances in data processing and storage have facilitated the acquisition of vast acoustic datasets through an increasing number of recording platforms, such as the Song Meter from Wildlife Acoustics, AURAL-M2 from Multi-Electronique and MARU from Cornell University. A comprehensive review of these and many others underwater sound recorders is given in [23] along with appropriate references. This has increased the amount of data to be analysed from individual minutes-long, MB-large audio recordings, to hundreds of GB, multi-month datasets. Processing of such long-term datasets requires a different approach to previous scrutiny of short, single recordings and automated data-mining software packages could provide the opportunity to do this. However, the advent of accessibility of underwater noise data as a sole or complementary data source also means that it is likely to be studied by researchers who may not be familiar with the physics behind underwater acoustics and acoustic signal processing. Thus, any processing package needs to be intuitive to those with little experience in acoustics.

Interrogation of long-term datasets requires the ability to view the entire set as a whole or in part, magnify any segment of interest to quantify signals (biotic or abiotic), across any given frequency range, and data-mine the entire dataset for said signals. It should be able to count signals, and display

their occurrence on a timescale marine fauna respond to (daylight, sunset etc.), figuratively illustrating diel, lunar, seasonal or annual patterns. Received levels (RMS and peak acoustic pressure and sound exposure levels) need to be quantified to classify these signals and trends. Currently, many software packages are available that can aid in scrutiny of individual, or short-term audio sets to analyse small numbers of signals or extract and save sounds (some examples being Audition from Adobe, Ishmael from CIMRS Bioacoustics Lab of Oregon State University and Raven from Cornell Lab of Ornithology). Some other software packages, such as PAMGUARD (<http://www.pamguard.org/>), Song Scope (<http://www.wildlifeacoustics.com/products/song-scope-overview>) and Acousonde (<http://www.acousonde.com>), provide means for automatic detection of particular sounds, primarily whale and dolphin sounds, in long-term sea noise recordings. While these packages have a number of advantages, they do not provide a full set of tools to quickly review multi-month datasets with respect to long-term changes in the sea noise spectrum and its biological or anthropogenic components and, at the same time, to comprehensively analyse acoustic characteristics of noise sources of particular interest. The aim of this study was to design, and continually develop an adaptable software tool to reflect all of these needs, in this case, a Matlab toolbox to aid the Characterisation Of Recorded Underwater Sound, "CHORUS".

TOOLBOX DESCRIPTION

The CHORUS toolbox is a library of Matlab routines with a Graphic User's Interface (GUI) designed at the Centre for Marine Science and Technology (CMST), Curtin University to simplify analysis of large (up to several hundred GB) sets of sea noise data. It is easy-to-use, even for researchers who are not proficient in Matlab programming. CHORUS is written as an open source code with a comprehensible structure, which allows an advanced Matlab user to add new modules (GUI features and functions) in a tree-like manner. It works with large sets of individual audio recordings repeated with a certain interval. Long continuous recordings can also be analysed with the toolbox. CHORUS accepts various formats of audio data, including Wave Audio Files (WAV) and binary files with and without headers and/or footers. For uncommon binary data formats, a special function should be written to export audio data into CHORUS. The complete process of acoustic data analysis is divided into two steps: (1) data pre-processing and (2) review of preliminary results with a comprehensive analysis of individual sea noise recordings, which is detailed in the following sections.

Data pre-processing

Preliminary processing of sea noise data involves computationally expensive and hence time consuming operations, which does not require the user's presence and expedites the post-processing data analysis. The pre-processing routines sort all recordings in a set in recording time order and calculate the Power Spectrum Density (PSD) averaged for each recording section of length chosen by the user. If the dataset consists of a large number of recordings and individual

recording are not too long, then the PSD averaging window is recommended to be of the length of the whole recording, which is a default setting. The PSD is calculated with a 1-Hz resolution from 0 Hz to the Nyquist frequency which is automatically determined from the sampling frequency of recording.

When starting data pre-processing, the user has to provide some data and select settings as follows:

Calibration data are needed to correct the resulting PSD of sea noise for the frequency response of the recording system. It can be provided in the following forms:

- Calibration file name (with full path) of a data file with a recording of a signal from a white noise generator input in series with the hydrophone and recorded in the same data format and with the same or higher sampling frequency as the raw data files with sea noise recordings. If such a calibration file exists and this option is chosen, then the user is asked to input the calibration noise level in dB re 1 V²/Hz;
- ASCII or .mat file with the frequency response of recording system in dB re data units/V_{in}, where the data units can be either bits or Volts representing the signal amplitude in the data files and V_{in} is the voltage at the hydrophone output. The frequency response data need to be provided up to at least the Nyquist frequency. If the frequency response in the calibration data is gridded with a coarser resolution than 1 Hz, it will be interpolated into a 1-Hz grid.
- If no calibration data are available, then the PSD will be calculated in relative units.
- Hydrophone sensitivity in dB re 1 V/μPa. This value is needed only if the frequency response data are available.
- Full path to the folder with raw data files.
- Length of signal sections (time window) in seconds to calculate PSD. If it is different from the length of each individual recording, then the section length is recommended to be such that the whole recording consists of an integer number of sections.
- Length of each output file in days with resulting PSD. This setting is required to limit the size of the output files with PSDs, which depends on frequency band of recording and PSD window length.

The output files contain matrices of PSD and vectors of the time and frequency grids used for calculation. If the calibration data and hydrophone sensitivity are provided, then the PSD data of sea noise are saved in μPa²/Hz.

Data review and analysis

The pre-processed data can be quickly reviewed and analysed using the CHORUS GUI toolbox. For analysis, both raw data files and pre-processed data with PSDs are needed. Before the toolbox opens its main GUI window, it asks the user to input the time zone in order to display all results in local time and the coordinates of sea noise recorder, if the sunrise and sunset times are needed to be displayed in the CHORUS graphs.

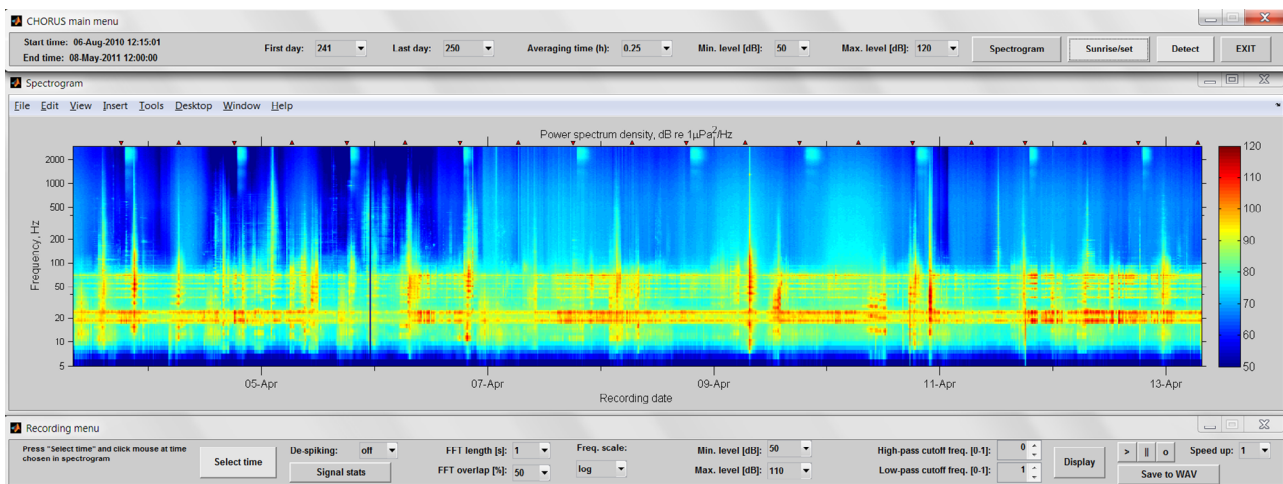


Figure 1: LTA spectrogram of sea noise recorded for 10 days compiled from PSDs of individual recordings. The red upward and downward triangles indicate the sunrise and sunset time respectively.

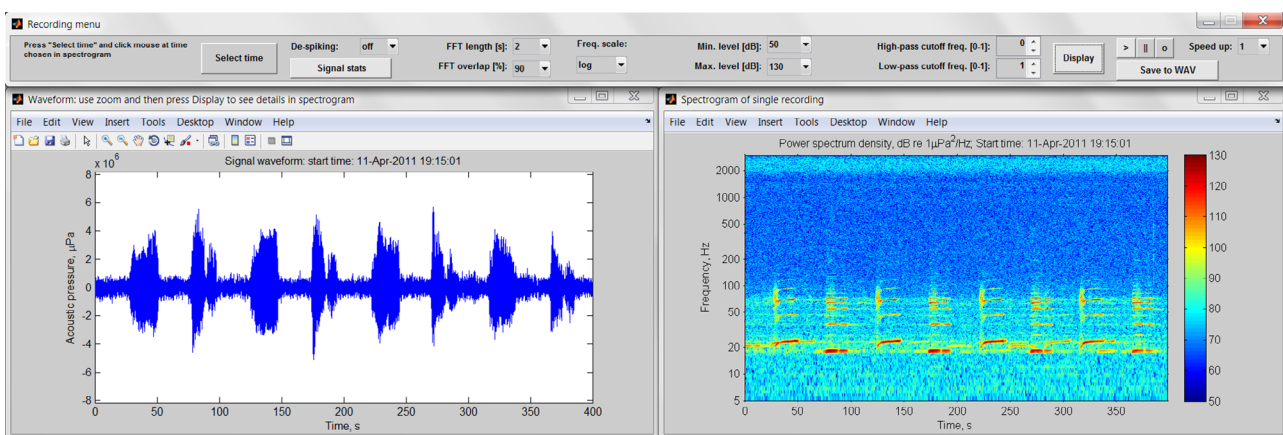


Figure 2: Recording menu (top panel) and waveform and spectrogram of selected recording (bottom left and right panels respectively), displaying blue whale calls.

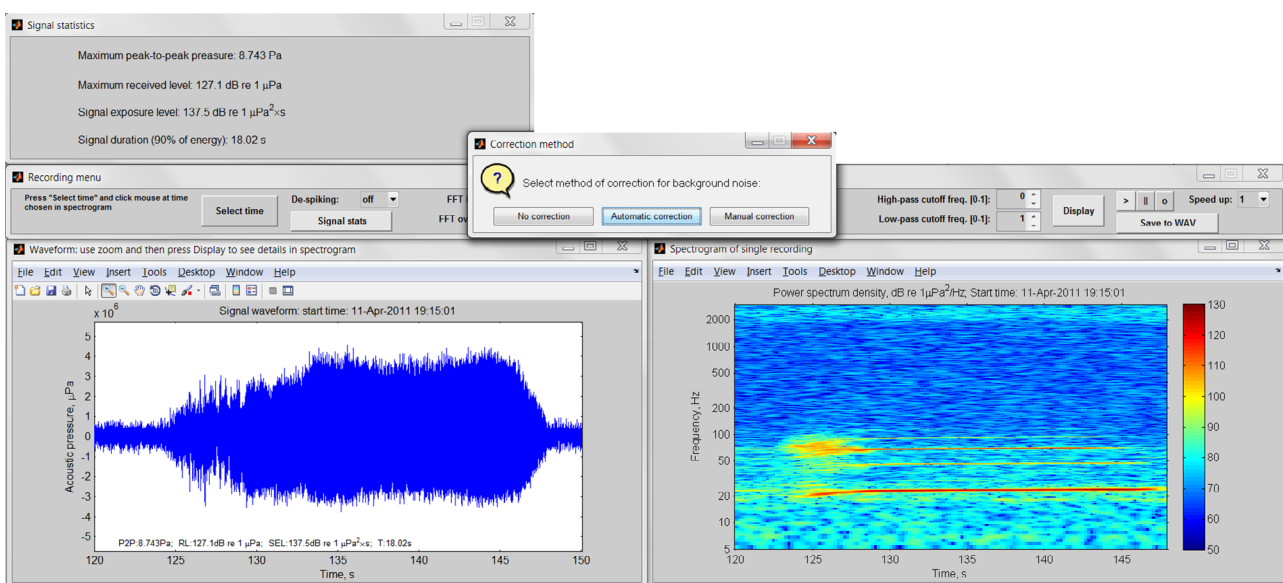


Figure 3: Waveform and spectrogram of a pygmy blue whale call localised in a sea noise recording (bottom panels), noise correction menu (middle panel) and signal statistics (top left panel)

The CHORUS GUI main menu appears at the top of the screen and displays the start and end dates and times of the whole dataset and user interface pop-up menus and push and radio buttons (Figure 1, top panel). The main menu controls parameters of a Long-Time Averaged (LTA) spectrogram to be displayed (middle panel in Figure 1). The LTA spectrogram is compiled from PSDs of individual recordings or signal sections chosen to calculate PSD data during pre-processing. It displays main spectral features of sea noise and their changes over a long time period of several days, which allows the user to quickly review the whole dataset of several months and identify the main contributors for a more detailed waveform and spectrum analysis. The user selects the first and last days of the time period from the dataset to be displayed in the LTA spectrogram. To display longer time periods, additional averaging of PSD may be needed by changing the averaging time in a pop-up menu. The averaging time can be chosen from one to four repetition periods of individual recordings (or length of section in a continuous recording chosen for PSD calculation). A logarithmic frequency scale is used to display the LTA spectrogram. The user can also adjust its colour-scale by selecting the minimum and maximum PSD levels in the corresponding pop-up menu. If coordinates of the recorder are entered at the program start, the sunrise and sunset time can be displayed by red triangle marks at the top of the LTA spectrogram. The times of new, full and quarter phases of the moon will also be displayed in the next version of the toolbox.

After pressing the “Spectrogram” button in the main menu, the LTA spectrogram is displayed with a Recording menu at the bottom of it (Figure 1, bottom panel). The Recording menu allows the user to select any time within the time period of the displayed LTA spectrogram and display the waveform and spectrogram of the recording (or recording section) made at that time. The waveform and spectrogram are displayed in two bottom panels, below the recording menu (Figure 2), after pressing the “Select time” button, clicking the mouse at the selected time in the LTA spectrogram and then pressing the “Display” button. The start time of recording is shown in the titles of the bottom panels.

The appearance of the waveform and spectrogram is controlled by setting the Recording menu, as shown in Figure 2. The signal can be low-pass, high-pass or band-pass filtered to highlight certain components of recorded noise. The spectrogram can be calculated using different FFT window length from 10 ms to 2 s and different overlap from 0% to 90%, depending on temporal and spectral characteristics of the signals to be satisfactorily displayed in the spectrogram. For example, long-lasting low-frequency tonal or quasi-tonal signals are displayed in a better way with a longer FFT window, while short impulsive signals need a short FFT window to be properly displayed in the spectrogram. The frequency scale of the spectrogram can be chosen to be either linear or logarithmic according to user’s preferences. If some part of the recorded signal needs to be displayed with more details, then the Matlab graphic zooming function can be used in the waveform window to select the time interval of interest. To update the waveform and spectrogram panels after any change

in the Recording menu settings or zooming, the user has to press the Display button again.

The sound playback submenu of the Recording menu, which includes play, pause and stop buttons, allows the user to listen to the sound of the whole recording or its selected part. The progress of sound play-back in time is shown in the waveform panel by a moving vertical bar. As acoustic frequencies of many natural sounds in sea noise, e.g. blue whale calls, are beyond the typical range of human auditory perception, the playback submenu also has an option to speed up the sound playback by 2, 5 or 10 times in order to increase the sound frequency accordingly.

If raw acoustic data were recorded in a special binary format, the whole recording or its selected part can be saved in the .WAV format acceptable for conventional sound players in MS Windows and its applications, such as Power Point.

Characteristics of transient and continuous signal of interest can be calculated using the Signal statistics submenu of the Recording menu. If the signal of interest is transient, the user localises the signal in the recording waveform by using the zooming function and updating the waveform panel. Pressing the “Signal stats” button opens the background noise correction menu (Figure 3), where the user is asked to select one of three methods for correction. For a continuous signal, no correction is needed. For a transient signal, the correction can be made either manually or automatically. In the manual mode, the user localises the waveform section containing only the background noise by clicking the mouse at the start and end of the section. In the automatic mode, the program automatically selects the waveform section with minimum acoustic power assuming that it represents the background noise power. The calculated characteristics are the maximum peak-to-peak acoustic pressure in Pa, the maximum received level in dB re 1 μ Pa, the signal exposure level in dB re 1 μ Pa²×s, and the signal duration in seconds based on 90% of its energy (relevant only to transient signals). The measurement data are displayed in a separate window and added in the bottom of the waveform panel (for reporting purposes), as shown in Figure 3.

Sea noise recorded on the coastal shelf, especially in shallow tropical waters, is often dominated by intense impulsive noise from snapping shrimp. This high-amplitude noise can distort significantly the waveform of other underwater signals which are of interest for special analysis, e.g. calculation of signal parameters. The Recording menu contains a submenu which turns a de-spiking function on with parameters selected by the user. An autoregression method for localisation and interpolation of outliers (spikes) in a waveform [24] is employed for de-spiking, so that the waveform of underlying signals distorted by spikes is reconstructed. The default parameters shown in Figure 4 are optimum for filtering out spikes from snapping shrimp. Other settings can be chosen for filtering out parasitic impulsive signals of different origin. After applying de-spiking to the waveform, the signal waveform before and after de-spiking are shown in the waveform panel by red and blue lines respectively. All subsequent operations and calculations, including signal statistics, are performed with the de-spiked signal.

Signal detection

Detection and characterisation of signals of certain origin in sea noise are a common procedure. The CHORUS toolbox provides means to implement this procedure. The main purposes of this CHORUS function is: (1) to test performance of a signal detector of certain type and (2) to process long-term datasets in order to detect acoustic signals of certain origin and assess their major characteristics, such as the frequency content, duration and intensity. The detection menu is called from the CHORUS main menu. It opens a popup menu with a list of underwater sound sources to be selected for detection. The current version of CHORUS offers only two sound sources: pygmy and Antarctic blue whale vocalisations which are common for the southern, western and partly eastern parts of Australia's continental shelf and slope. Humpback whale calls and toothed whale echolocation clicks are planned to be added soon in the source list. Moreover, the architecture of the CHORUS toolbox makes it easy to add automatic detectors of other sound sources without any alteration of the basic routines and functions of the toolbox.

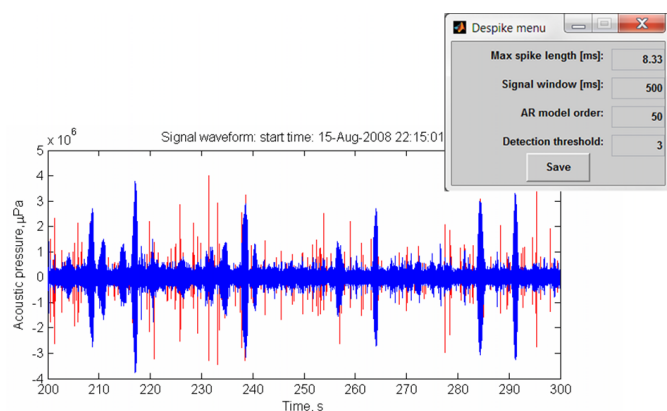


Figure 4: Waveform of sea noise with humpback whale calls before (red) and after (blue) de-spiking, which suppresses snapping shrimp noise. The top right panel shows settings of parameters in the de-spiking menu (see [24] for details of settings in the AR model).

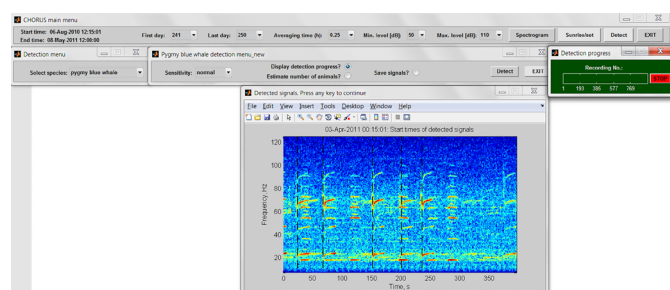


Figure 5: Detection menu with the window of detection settings for pygmy blue whale calls (unit 2 of whale song as described in [1]); sliding bar displaying progress of search over selected recording period (green panel) and spectrogram of an individual recording with the detection times indicated by the dashed vertical lines. The detector missed one of six targeted calls present in this particular recording (starting at about 370 s) and did not produce false detections.

Once the signal source is selected in the detection menu, a special Matlab routine with associated functions is called to implement automatic detection. The example given below is related to detection of calls from pygmy blue whales of the eastern Indian Ocean population that frequent waters off the western and southern Australian coast. Details of the detection method and its performance test are given in [1]. A similar approach can be implemented in the toolbox for other sources of underwater signals.

The detection routine opens a new window with settings governing the detection operation (Figure 5). Firstly, the sensitivity of detection has to be selected in order to control the proportion of missed detections and false alarms, as described in detail in [1]. The higher the sensitivity, the lower misdetection and higher false alarm rates will be. A trade-off between these two rates, when they are nearly equal, can be referred to as normal sensitivity. If the user wishes to control the detection results for verification purposes, then the spectrogram of individual recordings containing detection(s) is displayed with the detection times shown in the spectrogram (Figure 5, bottom panel). The detection operation is performed for the time period specified in the main menu by the first and last day. Once it is finished, the detection times are saved in a .MAT file along with other characteristics of detected signals, such as the signal frequency, RMS pressure and some others depending on signal type and functionality of the detector. Saving the waveform of detected signals can be useful for further verification, if the total number of expected detections is not too large. If the number of similar callers (or similar sources), making sound within the same recording period, can be estimated based on some criteria, then this number can also be saved. When processing large datasets spanning several months, it is useful to track the search progress over the observation time or recording number, using, for example, a separate window with a sliding bar, as shown in the green panel of Figure 5.

EXAMPLES OF RESULTS

Several tens of large datasets containing sea noise recordings from a few weeks to about a year long have been analysed for various purposes using the CHORUS toolbox. Employing CHORUS helps in preparing technical reports for industry and governmental agencies concerning with potential impacts of offshore industry operation on marine fauna. This includes measuring characteristics of natural sea noise and its components of physical and biological origin and assessing man-made noises resulting from offshore industrial and recreational activities. All panels with waveforms and spectrograms created by CHORUS can be easily copied and pasted into a MS Word document or a Power Point presentation.

CHORUS has also been extensively used for applied research in marine biology, underwater acoustics and oceanography. In particular, results of sea noise analysis with CHORUS have been used to study temporal and migratory patterns of various species of marine mammals and fish in several locations over the continental shelf and slope around Australia [2, 4, 6, 7, 8, 25-28]. As an example, the temporal and spatial patterns of pygmy blue whale migration off the western and southern coasts of Australia

are explored using data from several autonomous sea noise recorders deployed on the shelf, including the passive acoustic observatories of the Australian Integrated Marine Observing System (IMOS, [29]). These patterns are derived in particular from the presence and frequency of occurrence of vocalisations by pygmy blue whales detected at different locations using CHORUS. Figure 6 shows the frequency of occurrence of pygmy blue whale calls detected at the IMOS passive acoustic observatory in the Perth Canyon. The plot reveals the temporal pattern of whale migration in this area of the continental slope. The whales appear in this area from late November - early December to mid January, when they migrate primarily to feeding grounds in the Southern Ocean, and then from early February to June, when they migrate to their breeding grounds in the tropical waters [30]. On the northern leg, the whales tend to spend more time in the canyon region, as it is believed to be a good feeding spot for them [31], so that the number of detections during the northern migration period is considerably larger. The automatic detector of pygmy blue whale calls in CHORUS is capable of measuring the call frequencies. This has allowed us to reveal a long-term decline in the frequency of their calls of about 0.12 Hz/year for the fundamental frequency [20].

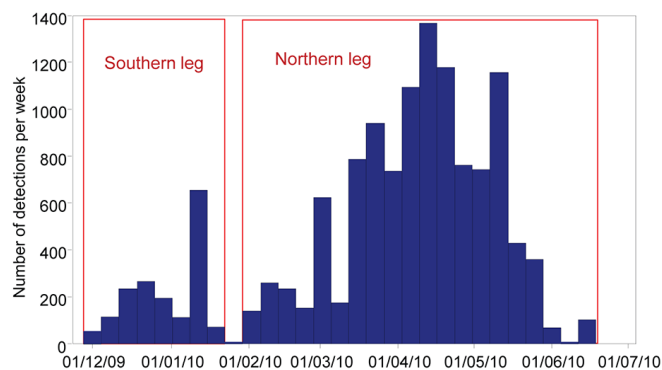


Figure 6: Histogram of the number of calls detected weekly at the IMOS acoustic observatory in the Perth Canyon from November 2009 to July 2010.

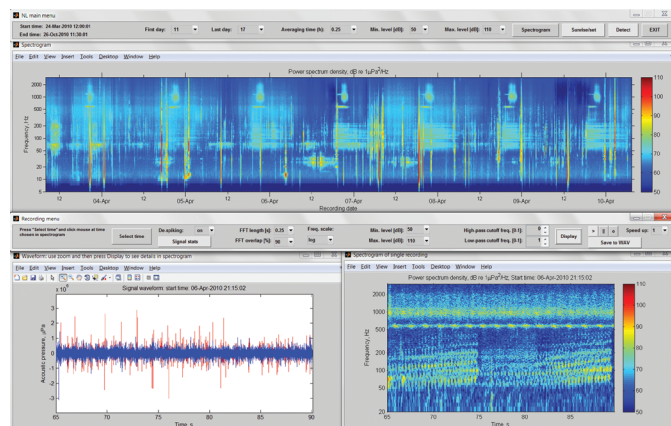


Figure 7. Stacked spectrogram of seven days of recording of fish choruses off the WA coast, produced using CHORUS (top panel) and waveform (bottom left panel) and spectrogram (bottom right panel) of a section of sea noise recording that contains sounds from two fish species.

Combining signal measurements of individual fish calls in CHORUS with single hydrophone localisation techniques [32, 33] has provided the source level of vocalisation by commercially important fish species [34]. Analysis of long-term datasets has been used to highlight the overlapping nature and periodicity of multiple fish choruses at a single location and infer movement of an aggregation over time [28]. Figure 7 illustrates how multiple fish choruses can occur with defined temporal patterns, at one location, over similar frequency bands. CHORUS helps quickly identify temporal patterns over a variety of timescales, and see how the callers might interact with each other. In this case, two fish choruses begin calling on the evening and call each evening for the following seven days (sound energy between roughly 500 and 2000 Hz), another chorus begins earlier in the day (sound energy between roughly 50 and 200 Hz), continuing through the night (Figure 7, main spectrogram panel). The bottom right panel shows how three of the choruses overlap closely in time, throughout the whole 15-second recording section and one fish producing the two upward sweeps beginning at around 65 and 83 s.

In acoustic modelling studies, specific characteristics of sound propagation over Australia's continental shelf have been investigated with the help of CHORUS [35].

CONCLUSIONS

The CHORUS toolbox has provided the basis to meet many needs of sea noise research and monitoring. Being under its fourth iteration it has also shown the ability to be revised simply to incorporate new aspects to acoustic ecology and quantification. This can be conducted on generic WAV files, generated by numerous recordings systems or the CMST-Defence Science and Technology developed sea noise loggers. An executable version of CHORUS will soon be available for academic purposes, particularly for processing IMOS data, for which the toolbox is most regularly used.

While the possibilities for development are numerous, the immediate future for CHORUS is anticipated to be an expansion of the detector functions to include other marine mammals and fish, and to export defined chorus levels of marine animals for long-term comparison with environmental and anthropogenic variables that may contribute to vocalisation levels.

ACKNOWLEDGEMENTS

The CHORUS toolbox has been driven by the use, requests and comments from several members of the CMST research group to meet the needs of those interrogating long-term datasets of sea noise. Special thanks to Dr Rob McCauley who formulated and developed the general concept of sea noise analysis. The contributions of the CMST researchers have, and will continue to, further the expansion and development of the toolbox.

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